Over 100 km of subsea tunnels have been constructed in Norway, and during the last ten years most of these have been for transport purposes, although some have also been built to bring pipelines ashore from the North Sea oil fields. Altogether more than 80 km of subsea tunnels have been constructed since 1980, as shown in Table I. More than 500 intakes in reservoirs have been made by submerged piercing: this Norwegian speciality, known as 'lake tap', is not dealt with in this article.

Among the subsea tunnel projects under construction in the summer of 1995 the following should be mentioned:

- Østfjord, a 3.3 km long two-lane road tunnel (80 m$^2$) in gneiss and gabbro with the deepest point 110 m below sea level. It has a maximum gradient of 1:12.
- Magerøy, a 6.8 km long two-lane (53 m$^2$) road tunnel in rocks of sedimentary origin (meta-greywacke, clay schist, sandstone) with the deepest point 220 m below sea level. It has a maximum gradient of 1:12.
- Bjørøy tunnel, a road tunnel with its lowest point 82 m below sea level. This tunnel has experienced very difficult ground conditions with highly permeable and partly unstable ground over a large part of its 2 km length.

Many possible subsea tunnel projects have been studied over the last 10 years, including three parallel 6 m diameter TBM tunnels 60 km long at 500 m depth to bring pipelines from a near offshore oil field to the Norwegian mainland$, and a 45 km long railway tunnel beneath a deep fjord.

**DESIGN**

All Norwegian subsea tunnels have been excavated by drill and blast and have achieved an average advance rate of 40-80 m/week. The total construction cost of a subsea road tunnel amounts to $4,500-10,000/m of tunnel, of which the excavation part (drill, blast and mucking out) constitutes about $1,500/m. The rock supporting works, which are designed for the rock mass conditions encountered in the tunnel, mainly consist of fibre-reinforced shotcrete and rock bolts.

The permanent water leakage amounts to 0.1-0.45 m$^3$/min/km of tunnel.

Over the past 40 years, Norwegian contractors have become some of the most skilled in hard-rock tunnelling. The many hundreds of kilometres of tunnel driven in connection with hydropower development, underground storage and transport have resulted in an accumulation of experience which is equalled in few other countries in the world. An important feature has been the willingness of the tunnelling
Table I: Subsea tunnels constructed in Norway after 1980 (revised after Ref. 1)

<table>
<thead>
<tr>
<th>TUNNEL</th>
<th>TYPE</th>
<th>YEAR</th>
<th>LENGTH</th>
<th>DEEPEST POINT</th>
<th>CROSS SECTION</th>
<th>ROCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slemestad</td>
<td>W</td>
<td>1980</td>
<td>1.0 km</td>
<td>-58 m</td>
<td>10 m²</td>
<td>clays, limestone</td>
</tr>
<tr>
<td>Vardø</td>
<td>R</td>
<td>1982</td>
<td>2.6 km</td>
<td>-88 m</td>
<td>46 m²</td>
<td>slate, sandstone</td>
</tr>
<tr>
<td>Kårstø</td>
<td>W</td>
<td>1988</td>
<td>0.4 km</td>
<td>-58 m</td>
<td>20 m²</td>
<td>phyllite</td>
</tr>
<tr>
<td>Karmundet</td>
<td>O</td>
<td>1984</td>
<td>4.7 km</td>
<td>-180 m</td>
<td>26 m²</td>
<td>gneiss, phyllite</td>
</tr>
<tr>
<td>Førdeisfjord</td>
<td>O</td>
<td>1984</td>
<td>3.4 km</td>
<td>-160 m</td>
<td>26 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Førlandsfjord</td>
<td>O</td>
<td>1984</td>
<td>3.9 km</td>
<td>-170 m</td>
<td>26 m²</td>
<td>gneiss, phyllite</td>
</tr>
<tr>
<td>Ellingsøy</td>
<td>R</td>
<td>1987</td>
<td>3.5 km</td>
<td>-140 m</td>
<td>88 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Valderøy</td>
<td>R</td>
<td>1987</td>
<td>4.2 km</td>
<td>-137 m</td>
<td>68 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Hjartøy</td>
<td>O</td>
<td>1987</td>
<td>2.5 km</td>
<td>-110 m</td>
<td>26 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Kvalsund</td>
<td>R</td>
<td>1988</td>
<td>1.5 km</td>
<td>-56 m</td>
<td>43 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Godøy</td>
<td>R</td>
<td>1988</td>
<td>3.8 km</td>
<td>-153 m</td>
<td>48 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Flekkerøy</td>
<td>R</td>
<td>1989</td>
<td>2.3 km</td>
<td>-101 m</td>
<td>46 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Hvaler</td>
<td>R</td>
<td>1989</td>
<td>3.8 km</td>
<td>-120 m</td>
<td>45 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Nappstruørn</td>
<td>R</td>
<td>1990</td>
<td>1.8 km</td>
<td>-60 m</td>
<td>56 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Maustrandt</td>
<td>R</td>
<td>1990</td>
<td>2.3 km</td>
<td>-93 m</td>
<td>43 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Fannefjord</td>
<td>R</td>
<td>1990</td>
<td>2.7 km</td>
<td>-100 m</td>
<td>43 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>IVAR, Jarven</td>
<td>W</td>
<td>1991</td>
<td>1.9 km</td>
<td>-80 m</td>
<td>20 m²</td>
<td>phyllite</td>
</tr>
<tr>
<td>Kalstø</td>
<td>O</td>
<td>1991</td>
<td>1.2 km</td>
<td>-106 m</td>
<td>38 m²</td>
<td>gneiss, phyllite</td>
</tr>
<tr>
<td>Ryfjord</td>
<td>R</td>
<td>1992</td>
<td>5.8 km</td>
<td>-223 m</td>
<td>70 m²</td>
<td>gneiss, phyllite</td>
</tr>
<tr>
<td>Måstrafløyrd</td>
<td>R</td>
<td>1992</td>
<td>4.4 km</td>
<td>-133 m</td>
<td>70 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Freifjord</td>
<td>R</td>
<td>1992</td>
<td>5.2 km</td>
<td>-130 m</td>
<td>70/54 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Tromsøyund</td>
<td>R</td>
<td>1994</td>
<td>3.4 km</td>
<td>-101 m</td>
<td>2 x 67 m²</td>
<td>dioritic gneiss</td>
</tr>
<tr>
<td>Hitra</td>
<td>R</td>
<td>1994</td>
<td>5.3 km</td>
<td>-357 m</td>
<td>70 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Troll</td>
<td>O</td>
<td>1995</td>
<td>3.8 km</td>
<td>-360 m</td>
<td>66 m²</td>
<td>gneiss</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>76.2 km</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R = Subsea road tunnel; W = Subsea water tunnel; O = Subsea tunnel for oil/gas pipeline

In addition to documentation of ground conditions, cross sections and gradients which are common for all tunnels, subsea tunnels require special design criteria. These are mainly related to the conditions mentioned in Table II. A special feature for subsea tunnels is the relatively steep gradient these tunnels have in order to reach the lowest point beneath the sea bed within shortest possible tunnel length. For road tunnels the maximum gradient is between 1:10 and 1:16, depending on the traffic load. For other tunnels the gradient is generally restricted to the limitations of the tunnelling equipment, which often is 1:7 for tunnel slopes less than 1 km and 1:9 for very long slopes.

GEOLOGY

Many engineers involved in tunnelling outside Scandinavia believe that all rock conditions in Norway are good. This is true on many occasions as the rocks found are 'hard rocks' - old igneous and metamorphic rocks with compressive strengths of more than 50 MPa. These ancient rocks have, however, suffered several periods of earth movement resulting in numerous faults, shear zones and thrust zones. Such features often cause great challenges and problems for tunnel excavation.

Another important feature of Scandinavian geology is the effect of the Ice Age. Erosion from the glacier activity 'cleaned' rock surfaces by removing weathered rocks, leaving fresh industry to accept new methods resulting in safer techniques and cost savings.

The alignment for a subsea tunnel is largely influenced by the geological and the topographical conditions as well as the requirement of the maximum gradient of the tunnel. The minimum safe distance between the tunnel roof and the rock surface under the sea (the rock cover) is a crucial dimension in locating a subsea tunnel. The minimum rock cover must be sufficiently thick to allow unexpected rock falls or cave-ins to occur without causing a critical situation in the tunnel. For road tunnels a minimum cover of 50 m is used during planning, until the results of detailed investigations are available. The rock cover requirements may be reduced to 40 m if the ground conditions are thoroughly documented to have a satisfactory quality (Fig. 1).

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The ground conditions are generally evaluated using exploratory investigations. The rock-mass conditions are determined by using geotechnical and geological investigations. The exploratory works performed during tunnel excavation are crucial for the evaluation of the rock-mass conditions. These are generally carried out at two stages:
- The field investigations made before tunnelling starts;
- The exploratory works performed during tunnel excavation.

First evaluations for the possible alignment for the subsea part of the tunnel are based on studies of geological and engineering mapping. The cost for these preliminary investigations is 1.5-5% of the construction cost. Subsea tunnels, where the majority of the rock and the surface are covered by water, require an extended investigation programme compared with ordinary "land" tunnels. Special investigation techniques have been developed to collect information on the rock mass conditions. These are generally carried out at two stages:
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Experience over the last 10 years of subsea tunnel construction is that the total cost for investigation is in the range of 2.6%-7% of the construction cost, and probe drilling amounts to 1.6%-2% (Fig. 4). As mentioned earlier, low figures are mainly due to information obtained from surface observations of exposed rock combined with the tunnelling experience and confidence in ground conditions.

CONSTRUCTION

All Norwegian subsea tunnels have been excavated by the drill-and-blast method. Successful tunnel driving depends heavily on craftsmanship and the flexible design adopted to the local ground conditions. Foreign visitors to Norwegian tunnel construction sites are often surprised that only three men are doing the drilling, blasting, mucking out and rock support works.

Usually there are two shifts each day working 5 days/week. Each shift is 10 hours: shift I from 0600 to 1600 and shift II from 1600 to 0200. In addition to the normal shift labour force there are a number of specialists who work daytime and the full tunnel crew of the main contractor consists of 12 persons. Table IV shows the normal division of tasks for the tunnel workers. Subcontractors traditionally transport the blasted rock from the face and usually supply all the concrete.

The management of the main contractor will vary according to the size and requirements of the project; as a rule four to six engineers are needed for a one-face job with an addition of three or four when tunnelling is carried out at two faces.

Table V shows the main equipment used apart from trucks for hauling out the rock, which as already noted is usually undertaken by a sub-contractor. All the equipment is generally subjected to severe corrosion by salt water which affects its performance and durability. This can largely be overcome by established routines to check, clean and protect exposed parts by special coatings.

**EXCAVATION**

Blasting rounds are usually drilled with 4.8.8.5 m long drill rods resulting in a round length of 4.2.4.5 m. The diameter of the holes is 43 mm and for the cut three to five uncharged holes are rounded to 75 100 mm. Some 90 to 100 charged holes/round are drilled to blast a two-lane road tunnel with cross section 60 m².

Special care is taken to achieve an accurate tunnel profile to minimise rock support and overbreak in blasted tunnels. The requirement for accuracy in positioning the holes is usually +/- 10 cm, with a direction deviation better than 5%. To meet this the drilling rig may be equipped with positioning and guidance systems and automatically follow a preset drilling pattern.

The explosive is usually ANFO, a mixture of ammonium nitrate and diesel oil. In addition to its low price, close to one quarter of ordinary dynamite, ANFO has safety benefits regarding storage. Production of the required amount of ANFO is carried out each shift.

Haulage of blasted rock out of the tunnel is in trucks with a loading capacity of 10-15 m³ chosen because of the relatively steep and long descending parts of the tunnel with gradients between 1:7 and 1:12. The number of vehicles varies from two to three in the outer part of the tunnel and increases by approximately one vehicle for each kilometre of tunnel length.

The time required for the various operations using 4.8 m long drilling rods (4.3 m round length) in a two-lane road tunnel is generally:

- **Scaling** 45 min
- **Drilling** (60 m² cross section) 2 h 30 min
- **Ventilation** 15 min
- **Mucking-out** 2 h 00 min
- **Total** 5 h 30 min
Though yielding of the tunnel surface has been recorded in some clay zones, instability from squeezing is not a problem encountered in Norwegian subsea tunnels. Nor have rock bursts caused significant problems.

The main principle is to design the rock support for the actual ground conditions encountered. This requires flexible support methods which can be quickly adjusted to meet the continuously changing quality of the rock. Such flexibility is achieved by the use of rock bolts, shotcrete and cast-in-place concrete lining, either alone or as an integral element of the support.

Norwegian contractors have long experience in using these types of support. Shotcrete, which today mainly is fibre reinforced, can be applied quickly and at a high capacity. Where reduction in the tunnel stability requires additional support, this is achieved by installing additional bolts or by adding shotcrete layers with or without fibre reinforcement.

Two methods are suitable for a number of ground conditions and are easily adapted to changing rockmass conditions. (Fig. 6)

Large faults or weakness zones with highly unstable rockmasses may be supported by a cast-in-place concrete lining, using a full lining shield designed to fit the actual cross section of the tunnel. Normally it takes only two to four hours from taking the decision to use this type of support until concrete casting can start. In adverse rock conditions with short stand-up times, shotcreting can be carried out shortly after blasting and then a concrete lining installed as a permanent support.

The rock support evaluations are partly based on experience from tunnels in the same region and partly by using the Q-system. As the underground conditions are never known until they are revealed during excavation, final decisions about the amount and methods for rock support are not taken before they can be studied in the tunnel. The supporting works are carried out in two main stages:

- Initial support. The amount is determined by the tunnel miners and their foremen.
- Permanent support. This is carried out to meet the requirements for satisfactory functioning of the tunnel during its life, and is determined after excavation by engineering geologists who must consider the long-term behaviour of the rock masses. Based on the results from mapping of the ground conditions in the tunnel the amount and types of support can be found according to the Q-system.

The types of support used for initial and permanent support are generally selected so that they may be combined. In this way the initial support to secure safe working conditions for the tunnelling crew can be included as a part of the permanent support. The latter is therefore installed only where it is necessary to strengthen the initial support.

The salt environment in subsea tunnels requires resistant materials. Thus concrete structures, including sprayed concrete (shotcrete), are made of concrete according to environmental class MA (very aggressive) as specified in the Norwegian standard NS 427A. Rock bolts of normal steel quality may be used, but stringent demands are made on the anti-corrosive coatings for bolts used in a salt water zone, and bolts are treated with a combination of hot-dip galvanisation, minimum thickness 80 microns and powder lacquering with epoxy, or a coating that gives comparable protection.

CONCLUSIONS

A key to successful construction of subsea projects in Norway has been the continuous exchange of experience and the close cooperation between the engineering geologists, the designers and the contractors. This has contributed to tunnelling advances of 40-80 m/week and low excavation costs (Fig. 7). Experience from seven subsea tunnels proved that the permanent water inflow varies between 100 - 450 litres/min per km of tunnel.

Using the two-lane Fjordfjord tunnel as an example of a typical Norwegian subsea road tunnel, the total costs including excavation, rock support, sealing works (grouting) and installations are $5,000/m.

REFERENCES


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